Survey on the Future Aeronautical Communication System and Its Development for Continental Communications

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Abstract

We present in this survey new technologies proposed for the evolution of the aeronautical communication infrastructure. Motivated by studies that estimate a growth of the air traffic flow, **a joint Euro-American project was launched in 2004** to provide solutions adapted to the future aeronautical scenario (air-air communication, traffic optimization...). This project is entitled aeronautical Future Communication System (FCS) and is composed by researchers, industrials and aeronautical authorities from many countries around the world. Inside the scope of this project, it has been developed a system called L-band Digital Aeronautical Communication System (L-DACS) to face the saturation of the current continental aeronautical communication system that operates in the VHF band. Since 2007, the L-DACS is being developed and two candidates were pre-selected: L-DACS1 and L-DACS2. In this work, we discuss about the FCS and the particularities of both pre-selected L-DACS candidates, comparing their benefits with the current aeronautical system. Some insights about their physical and medium access layers are also detailed and the project status is presented. Finally, the last part of this

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paper is dedicated to address the challenges on the development of the FCS/L-DACS.

Index Terms

Aeronautical communications, Future Communication System (FCS), L-band Digital Aeronautical Communication System (L-DACS), Radiofrequency (RF), Electromagnetic Interference (EMI), Electromagnetic Compatibility (EMC).

I. INTRODUCTION

In 2002, the need to improve the aeronautical communication system for air traffic management and air traffic control was recognized by the International Civil Aviation Organization (ICAO). This official organization affiliated to the United Nations was created in April 1947 [1] and comprises nowadays more than 180 country members. The ICAO is an important actor for the standardization of airspace control. Among other missions, the organization is responsible for the definition of the technology used for aeronautical communications and manages the aeronautical radio frequency spectrum [2].

The continental aeronautical communication is mainly ensured by the combination of two systems deployed in the Very High Frequency (VHF) aeronautical band (from 118 to 137 MHz). One of them is an **analogue** system developed for voice transmissions that has been in use for more than half a century [3]. The second one is a digital system recently introduced that enables data transmission [4]. Despite this latter evolution, current aeronautical communication systems seem to be insufficient to accommodate the traffic increase of the coming years. According to aviation authorities [5], the air traffic is estimated to grow 3% per year. Thus, the traffic load in early 2030 should be more than twice when compared to the load in 2005. Based on these estimations, the current system will suffer from severe congestion in some regions around the globe. For this reason and taking into account the evolution of wireless communication technologies, new requirements such as high data rate links, automatization procedures and air-to-air communication have been considered [6], [7] to the evolution of the continental aeronautical communication. Some improvements for the legacy systems were proposed [8]–[15] but none of them could provide a long term solution (beyond 2020).

In this context, **a joint Euro-American project was launched in 2004 in support to**

ICAO discussions to develop a Future Communication System that will complete the existing technology and provide a suitable solution based on the new aeronautical requirements. **The development of the Future Communication System** is now part of two programs: the Next Generation Air Transportation System (NextGen) [16], [17] lead by the US Federal Aviation Administration (FAA) and the Single European Sky ATM Research (SESAR) [18]. It involves a large number of research teams as well as industrial partners and aeronautical authorities from many countries. So far, numerous technologies have been considered to the Future Communication System (FCS) infrastructure and evaluated in agreement with the aeronautical requirements [19]–[22]. These evaluations allowed the identification of potential solutions [23]–[25] but no single technology could outperform all the other options with respect to the chosen criteria [19].

The L-band Digital Aeronautical Communication System (L-DACS) is the system in the FCS for L-band continental communications. Different from the current systems operating in the VHF aeronautical band, L-DACS is foreseen to provide interesting additional features such as a higher data rate. The band 960-1164 MHz was allocated to the Aeronautical Mobile (Route) Service (AM(R)S) in the Radio Regulations of the International Telecommunication Union (ITU) to enable the introduction of L-band aeronautical safety communication system. Some studies have been carried out to identify the L-DACS technologies that will support this service. Two proposals have been pre-selected. The first candidate named L-DACS1 [26], derived from **IEEE 802.16 wireless system**, is an evolution of the Broadband Aeronautical Multi-carrier Communication (B-AMC) standard [27] and the Telecommunications Industry Association Standard 902 (TIA-902) [28], also known as the Public Safety Communications Standard APCO Project 34 (P34). The second candidate called L-DACS2 [29], derived from the Global System for Mobile communications (GSM), is based on the All-purpose Multi-channel Aviation Communication System standard (AMACS) [30] and the L-band Data Link (LDL). The candidate systems fulfill most of the requirements expressed by the aeronautical community but are quite different and the final choice between the two L-DACS options should be made by the ICAO at the end of 2013, depending on the SESAR workplan.

Before the L-DACS technology choice, in-depth studies are required to compare the capabilities of both proposals. Current L-DACS investigations are focused on developing specifications [26], [29] and prototypes [31], [32] for both transmitters and receivers, as well as testing their performance in relevant aeronautical environments through Electromagnetic Compatibility

(EMC) studies. Indeed, the EMC of L-DACS with all systems operating in the L-band or in adjacent bands is very important due to flight safety [33].

These studies carried until now were crucial but not sufficient to select the L-DACS technology. Independently of the final decision, the L-DACS system must actually overcome numerous challenges for further stages in its development process. The L-DACS solution should accommodate continuously the air traffic growth and must be developed in a multinational cooperative context. In addition, for sake of viability, L-DACS **must be** standardized world-wide and its deployment should have a small impact on the aircraft building process.

Hence, this paper aims to present the L-DACS candidates and describe their advantages and limitations when compared with the legacy VHF system. This paper is organized as follows. Section II presents the current continental communication system used by aviation in the VHF band and the motivations and objectives of the FCS are discussed. Then, we provide an overview of the achieved steps of the joint Euro-American project for the development of the Future Communications Infrastructure (FCI) in Section III. After that, Section IV focuses on the description of the L-DACS candidates. After giving the principal reasons behind choosing L-DACS, we give a deeper insight on both L-DACS proposals through a comparative study regarding the physical and the medium access control layers. Section V provides an overview of the main research axes leading the current investigations on the L-DACS candidate systems. Finally, we present some challenges that L-DACS has to overcome for the future development and implementation stages.

II. Why a new system for aeronautical mobile communications?

Civil air traffic control communications and **air** traffic management communications in continental areas are mainly supported by the combination of two narrowband communication systems that operate on the aeronautical portion of the VHF band, between 118 MHz and 137 MHz. Both systems are based on the communication between the ground and the aircrafts and are used by civil aviation. The first and main system that guarantees the air traffic control communication is an analog-based system that employs a Double Side-Band Amplitude Modulation (DSB-AM). This system allows voice communication and it is being used for more than 70 years. In the 1990s, a new system was introduced to provide data transmission and **to allow air-ground message exchanges for the purpose of air traffic management**. Different technologies are employed for the data system, such as the VHF Digital Link (VDL) [11] and the Aircraft Communication Addressing and Reporting System (ACARS) [34]. Nowadays, with the feature to transmit voice and data messages simultaneously, the pilots are better assisted to conduct their flights.

Even with the recent evolution of the aeronautical VHF technology, current VHF systems are reaching their capacity limits and would not accommodate the increase of the **air traffic** around the world [35]. According to the forecasts [5], after 2011 the traffic will increase at least by a factor of by 3% per year, which means that the current system will suffer from severe congestion in some regions around the globe due to high traffic load [11]. In these conditions, as the air traffic volume increases, more airplanes will require one or several VHF radio frequencies for communications. Due to susceptibility of VHF **analogue** technology to background noise and interference, the quality of communication is likely to degrade below acceptable limits if the frequency congestion is not carefully managed. The technology, in use for decades, was conceived to provide voice services and it **cannot be adapted** to **data link applications**. Current other technologies have relatively low data rates and this also limits the possibilities of implementing new sets of services and features on such systems.

From the technological perspective, telecommunication systems are evolving and high-data-rate links are fundamental to provide advanced services that would be very useful for air control safety. Higher-data-rate solutions would enable additional features that would provide better safety systems and support automatic communication, pilot assistance and air traffic optimization. For these reasons, technology improvement is fundamental to be able to provide a long-term solution to the air traffic growth **presented in** the Communications Operating Concepts and Requirements (COCR) reports [6], [7].

Some solutions have been considered and studied so far. The first idea is to increase the network capacity by reducing transmission channel bandwidths [8]. However, in case of digital systems, this induces degradation on system data rate. The second approach is to develop an overlay technology in the VHF aeronautical band, *i.e.* a technology which shares the same frequency band with legacy VHF systems [9]–[15]. The problem with this method is the high interference levels that can be generated over the current system and endanger its reliability. These two options **may not meet** the long term aeronautical requirements, given the congestion of the VHF band. According to [36], these potential improvements may have been sufficient only for short and medium terms. Therefore, in the prospect to find a long term solution to cope with VHF band saturation, they have not been retained.

In this very specific context, the aeronautical community **has indicated a preference for** a new data communication system that will be able to coexist with the VHF system and will be adapted to the new traffic requirements. The idea lies on the preparation of the aeronautical communication to accommodate the traffic growth in the long term based on new communication technologies [36]. The future system is foreseen to support capacity demand for both voice and data beyond the traffic estimations for the future years and it is expected to provide air/air and air/ground communications.

The initial spectrum requirements were initially calculated in 2003 by LS-TELECOM (in cooperation with EUROCONTROL) [37], assuming an exemplary system using CDMA technology (because at that moment, the system technology was not yet known). These requirements were updated in 2006 in the COCR document [6] where the exact capacity per user was calculated through evaluation scenarios. Other requirements (such as latency, integrity per service...) were also formulated in the finalized COCR version published in 2007 [7].

As the aeronautical authorities forecast that the use of data communications will increase, the FCS will allow greater information exchange between aircraft and ground systems to achieve better Air Traffic Management (ATM). For example, some autonomous operations should take place in some parts of the airspace. Based on these requirements, the amount of communication traffic that the FCS is expected to support was calculated in the COCR [7] for several representative operational volumes like the Terminal Manoeuvring Area (TMA) or the continental en-route (ENR) area. It should be noticed that these technical requirements were provided from operational requirements independent from any specific technology and that the traffic growth was taken into account using prediction tools [7]. For the FCS development project, emphasis has been put in data-communications, and digital voice will be considered in next steps.

In addition, to support the different services within this future data-link system, a research program named NEtWorking the SKY (NEWSKY) was developed from February 2007 to October 2009 [38], [39] and aimed to define an IP based network architecture [40], [41] to ensure both safety-related and non-safety-related services.

III. FCI DEVELOPMENT ACTIVITIES FROM 2004 TO 2009

Recognizing that there is an insufficient spectrum in the VHF band to support future aeronautical communications needs, **EUROCONTROL and the US FAA** coordinated a joint development activity in 2004 in support of ICAO discussions. This initiative is known as the Future Communications Study and was started with a Cooperative Research Agreement named Action Plan 17 (AP-17). The objective was to identify the adapted technologies to support the FCI in the timeframe of 2020 and beyond and that fulfill the aviation needs **formulated in the COCR [7]**.

The **development of the future communication system** is now a part of two parallel research programs looking for (among other issues) a general solution allowing a long term communication infrastructure in the different regions of the world. One of these programs is named NextGen [16], [17]. It is lead by the US FAA and supported by the National Aeronautics and Space Administration (NASA). The other program is called SESAR [18]. **It is supported by EUROCONTROL,** the European Union (EU), Air Navigation Service Providers (ANSPs) as well as institutional and industrial partners. More recently (in 2008), a Japanese team from the Electronic Navigation Research Institute (ENRI) **started developing research activities in parallel to the two programs [42], [43].**

A. Overview

The Future Communication Study seeks for a solution in the long term considering among other reasons, that the technology improvements in the VHF band will be insufficient. Therefore, both programs focus on the introduction of new technologies to the FCI, based on three main phases. The first phase aims at identifying the most promising technologies to support this infrastructure by the assessment of a wide range of potential technologies: cellular system standards, IEEE wireless standards, public safety radio technologies, aviation specific technologies and military radio systems [19]. The second phase consists of the development of the identified technologies, from technology transition concepts to implementation strategies. Finally, the third phase is to build the new infrastructure at a wide scale not only in Europe and the US but also all over the world.

The first phase (*i.e.* technology assessment) of the FCS development was completed in 2007 and, for the moment, the second phase is in progress. We detail in the following paragraphs the methodology and results of that first development phase.

According to [44], the list of investigated technologies comprises cellular telephony derivatives (including 3G technologies like W-CDMA and UMTS), IEEE 802 wireless derivatives, Public Safety and Specialized Mobile Radios, Custom Narrowband VHF solutions, Custom Broadband, military and APC telephony. For the technology assessment, eleven criteria based on the COCR are used to compare the capabilities of all the existing technologies (around fifty) [19]. Two categories are identified: the technical criteria and the viability criteria. The technical criteria are related to system performance and the viability criteria address cost and risk elements associated to its implementation. The list of the eleven retained criteria can be found in [19].

The technologies are first screened considering only essential criteria, which are very important because without them, a technology can never be deployed. For instance, many aeronautical systems are already in operation both on the ground and in **aircraft**. Therefore, to ensure the flight safety, the functioning of existing equipments should not be altered by the deployment of a new system. In addition, the target technology is foreseen to be used in many countries in the world, which means that the future system must be open to international standardization. From the screening process, the emerging technologies are then evaluated by applying all the criteria weighted to their relative importance. In [19], two weighting approaches are proposed. In the first approach, a qualitative ranking of the criteria is performed and organized into three classes: important (not specifically addressed), very important (addressed for the viability of the technology) or most important (addressed for the applicability of the technology). In the second approach, criteria ranking based on Analytical Hierarchy Process (AHP) is performed based on some desirable features from technology attributes.

From 2004 to 2007, **EUROCONTROL and the FAA** performed a cooperative work to assess the different existing technologies. The activities were coordinated and presented to the ICAO Aeronautical Communication Panel (ACP) for international acceptance [23]–[25].

According to the first evaluation results [45], [46], the FCI will use complementary technologies across multiple frequency bands to provide the data and voice communication. The requirements depend on the aeronautical flight domains (airport surface, oceanic/remote airspace and continental/terrestrial airspace) and the most **suitable** frequency bands to each flight domain were identified depending on propagation conditions:

- Airport surface communications: C-band due to the limited propagation distance and high data rate, supported by an AM(R)S allocation in the Radio Regulation of the ITU limited to the ground,

- Continental communications (Airport area, TMA and En Route airspaces): in addition to the VHF band, the L-Band due to the potential spectrum availability and the **suitable L-band propagation characteristics [19],** supported by an AM(R)S allocation in the Radio Regulation of the ITU,
- Oceanic and remote communications: L-band supported by an Aeronautical Mobile Satellite (Route) Service allocation in the Radio Regulation of the ITU, for aeronautical beyond line of sight systems.

The screening results emphasize a significant overlap between the European and the American technology shortlists for all the domains (see [44], [47]). The technologies were classified into two general categories: technologies in continental airspace and technologies in specific flight domain (oceanic/remote airspace and airport surface).

One single candidate was **retained** in the shortlist for airport surface **[19], [44], [48], [49]. In fact, the candidate technologies for this flight domain are required to provide high-data-rate communications within limited-range [44] and the IEEE 802.16 has been recognized as the technology with the best performance for airport surface and terminal domains.** Consequently, the application of all the criteria to discriminate among other technologies was meaningless [19].

The application of all the criteria was also useless for the two satellite systems/concepts identified for oceanic/remote airspace [19] **because, as mentioned in [19], the "timeframe of the COCR operational concept is beyond the service horizon of current satellite systems". Therefore, research activities are being currently made to develop a "follow-on or custom satellite solution" (*i.e.* custom-designed satellite implementation specifically designed for aeronautical communications) fulfilling the aeronautical requirements.**

The whole-criteria studies were indeed focused on the proposed solutions for the continental domain. The evaluation results for both qualitative and AHP weighting methods are given in [19]. **For this flight domain, all the emerged technologies from the assessment process were data-link candidates, and their performance were evaluated in the L-band [20]. Among these technologies, the Wideband Code Division Multiple Access (W-CDMA) technology was not selected due to its impracticality to deploy (according to [20], a full complement of W-**

CDMA functional elements is required to satisfy aeronautical requirements). Furthermore, it was recognized that a future satellite solution may be able to support continental environments possibly complementing terrestrial systems.

From these results, the European and American teams developed the same technology recommendations for the different flight domains in [23]–[25]:

- Airport surface: Aeronautical Mobile Airport Communications System (AeroMACS) based on IEEE 802.16e standard in the C-band,
- Oceanic and desert communications: Next Generation Satellite system in the AMS(R)S band,
- Continental communications: In addition to systems in the VHF band, data-link system in the L-band, **possibly complemented by Next Generation Satellite Systems.**

Using the technology assessment results, a first joint roadmap (see Fig. 1) was developed to structure the implementation and evolution of aeronautical mobile communications with respect to traffic requirements. The FCI technologies for specific flight domains are identified whereas further studies are needed to determine the best technology to be used for continental communications. Indeed, for this flight domain, **the L-band is a challenging environment because of the current spectral occupation by numerous aeronautical systems and other systems in the immediate adjacent bands.** That is why it is very important to focus on the potential usage of the L-band for the FCI.

B. The current status: L-DACS investigations

The L-band data-link system identified in the **FCS** to support the FCI in continental areas is named the L-DACS. Different from the existing VHF systems, L-DACS includes features such as a higher data rate and it also complies with most of the air traffic requirements expressed by the aeronautical community [6], [7].

Among other needs, L-DACS has to cover very long distances (nearly 400 km) and to support very high mobility (up to 1080 km/h) [50]. L-DACS performance requirements are evaluated based on information from [7] for the different operational volumes (such as TMA and ENR). In particular, this evaluation includes Peak Instantaneous Aircrafts Counts ($PIACs$) per volume, Maximum airspeed in $Knots\ True\ Air\ Speed$ ($KTAS$) per

volume and most stringent capacity requirements in $kbps$ **(exact values can be found in [50]).**

In November 2007, the World Radiocommunications Conference (WRC) organized by the ITU decided a new AM(R)S allocation in a part of the L-Band (from 960 to 1164 MHz), primarily allocated to the Aeronautical Radionavigation Service (ARNS) [51]. This allocation has been made to support the L-DACS development in this band.

In parallel, some additional studies have been carried out to determine the most **suitable** technologies to support L-DACS services in this frequency band. Using the technology assessment process results and for sake of a harmonized technology, **the EUROCONTROL has initiated the development of two candidate systems** named L-DACS1 [26] and L-DACS2 [29].

The development of L-DACS candidates involves researchers, industrial partners and aviation authorities from many countries in the world. In addition, the **L-DACS development activities** follow a precise roadmap including a conception phase, a development phase and a deployment phase (see [52]). It should now be updated taking into account the development activities advancement in the recent months and it is also likely to be updated again in the coming years.

Currently, in depth-studies are being performed to choose the final L-DACS technology to be developed and implemented in the FCI. In the two next sections of this paper, we first present the origins and the main characteristics of the two pre-selected candidates, and then we provide a better insight on the studies that have been carried out from 2007 to now.

IV. The two L-DACS candidate systems

In this section, we focus on the description of the main characteristics of the two L-DACS candidates. We mention the benefits of L-DACS compared to current VHF technologies and we address the Physical (PHY) and the Medium Access Control (MAC) layers of the Open System Interconnection (OSI) reference model. We emphasize that although some significant similarities **exist**, the L-DACS candidate systems are quite different.

Let us first detail the technologies behind each L-DACS proposal. L-DACS1 [26] is derived from the **IEEE 802.16** wireless standard, which is one of the most widely deployed wireless technologies [53]. One of the original standards of L-DACS1 is the B-AMC standard [27] developed in Europe and based on the Broadband VHF (B-VHF) system [10]. The other is the

P34, developed in the US and based on the TIA-902 [28]. L-DACS2 [29] is inspired from the commercial GSM standard, which is the most popular standard for mobile telephone systems in the world. L-DACS2 is originated from two standards: the AMACS [30] developed in Europe and the LDL developed in the US.

Both L-DACS candidates take advantage from the most promising existing technologies. While L-DACS1 relies on modern modulation techniques and advanced network protocols used in the existing commercial standards, L-DACS2 capitalizes on experience from aviation specific standards using protocols that provide high quality-of-service communications.

Having the possibility to employ **the same type of antennas** already in use by other aeronautical systems is also among the potential strengths of L-DACS. The system will provide high quality of service communication in each coverage volume and for each flight domain, based on robust modulations and coding schemes [53]–[55].

A. PHY layer characteristics

1) The similarities: First of all, both candidates will employ **conventional aeronautical L-band antennas**. Indeed, these antennas are also used by aeronautical radionavigation systems already in operation, which means that their use will decrease the costs of the L-DACS deployment. Such antennas are omnidirectional in the azimuthal plane and their radiation patterns depend strongly on the elevation angle, referenced at the horizontal plane.

The typical airborne antenna gains are given by [56] for elevation angles between -90 and 90 degrees. The airborne antenna maximum gain is 5.4 dBi according to [57]. In addition, the expected ground antenna gains are determined by [58] for elevation angles between -90 and 90 degrees and the maximum ground antenna gain is 8 dBi. In addition, both L-DACS candidates have **comparable operational ranges** in Nautical Miles (NM).

2) The differences: **L-DACS1 and L-DACS2 have different required system performance in terms of residual Bit Error Rate (BER), inferred from [26], [29] (see Table I). It should be noticed that the residual BER represents the BER after applying error correction codes to received signals.** In addition, both L-DACS systems are foreseen to operate in distinct frequency bands. The L-DACS1 proposed frequency band would cover some parts of the 960 - 1009 MHz spectrum for ground transmissions and some parts of the 1048 - 1164 MHz band for mobile transmissions, knowing that the separation between the transmitting and receiving center frequencies is initially proposed to be set to 63 MHz. However, the expected spectrum for L-DACS2 would be 960.5 - 975 MHz, considering at present **a minimum 0.5** MHz **guard band** for sake of reducing the mutual interference with mobile telephony signals coming from base stations, which occupy the 925 - 960 MHz band.

Not only frequency ranges but also modulation schemes are different. **L-DACS1** is based on an Orthogonal Frequency Division Multiplexing (OFDM) modulation with Quadratic Phase Shift Keying (QPSK) mapped symbols, whereas L-DACS2 is characterized by a differential Gaussian Minimum Shift Keying (GMSK) modulation on binary symbols (see Table I). **Moreover, based on their specifications,** L-DACS devices are not expected to use the same effective bandwidth and power to transmit their respective signals (see Table I).

For sake of protection against electromagnetic radiations to other systems, L-DACS1 and L-DACS2 masks limit the unwanted power to ensure that out of band and spurious transmission levels (see Fig. 2) remain lower than thresholds specified by [59]. Due to different transmit powers and bandwidths, transmission masks are specific for each candidate system.

Divergences between L-DACS1 and L-DACS2 are noticed not only in the transmit mode but also in their receiving functions. Actually, the specifications of L-DACS candidates also present some differences in the receivers' parameters (see Table I). Both L-DACS receiving masks have not been defined yet and that they will be determined based on experiments in further steps of the L-DACS **development**. However, a first approximation can be to consider that the receiving mask and the transmitting mask would be similar.

So far, we detailed the main divergences between L-DACS1 and L-DACS2 with respect to system-parameters. We also mention herein a principal distinction addressing the duplexing technique, which qualifies how L-DACS terminals access to the transmission channels. While L-DACS1 employs a Frequency Division Duplex (FDD), L-DACS2 uses a Time Division Duplex (TDD). In the first case, the Ground Station (GS) and the Mobile Station (MS) can transmit simultaneously but using different carrier frequencies, whereas in the second case, the GS and the MS can use the same frequency channel to transmit but during disjoint time intervals. From these definitions, we show in the next subsection the effect of this parameter on the organization of the L-DACS communication.

B. MAC layer characteristics

1) The similarities: **The L-DACS communication is basically ensured by exchange of messages between a GS and a MS in its operational coverage. Information coming from the GS are transmitted via the Forward Link (FL) and those from the MS via the Reverse Link (RL). The communication is ensured by a succession of frames, a frame being a unit for information transmission between a GS and each MS in its coverage.**

For both candidates, the evolution of the communication between a MS and a GS can be represented by six successive steps. The first three steps are executed only once, during the cell entry, whereas the remaining steps will be repeated several times, during the aircraft dwell time within the cell.

In the first step, a MS listens to the framing message broadcasted by the GS to all covered MSs and containing its configuration information. In the second step, the MS requests a connection to the GS. In the third step, the GS acknowledges this request, gives a local address and allocates an available slot to the connected MS. In the fourth step, the MS formulates to the GS the needed resources to transmit its message. More precisely, if a connected MS does not transmit data, it transmits regularly a Keep Alive (KA) message in these parts. In the fifth step, the GS acknowledges the MS demand and indicates the position of the requested resources (if available) in the frame, to be used for this MS transmission. If the available resource is insufficient, the remaining slots will be allocated in the next transmission unit. In the sixth step, the MS transmits its RL message using the resource allocated by the GS.

For both L-DACS proposals, the communication with the current GS may end due to two events. In the first situation, the MS initiates a handover process to communicate with the GS of a neighboring cell or initiates a disconnection of the L-DACS network. In the second situation, the MS does not transmit data and the GS does not receive a KA message.

2) The differences: **Because of L-DACS candidate systems duplexing technique divergence, their MAC layers are differently structured. Indeed, while the FL and RL are operating simultaneously for L-DACS1, the L-DACS2 communication is based on alternation between RL and FL messages. For L-DACS1, the communication is organized into**

240 ms Superframes (SF) as mentioned in [26] and whose beginning and end are aligned in the FL and RL directions from the view of the GS. However, the L-DACS2 communication is organized into one-second successive frames [29].

Because of the L-DACS candidates system duplexing technique divergence, their frames are differently structured (see Fig. 6 for L-DACS1 and Fig. 7 for L-DACS2). On the one hand, a SF in the FL direction is composed by a 6.72 ms Brodacast (BC) frame followed by four 58.32 ms Multiframes (MF). The parallel SF in the RL direction is formed by a 6.72 ms Random Access (RA) frame then four 58.32 ms MF. The BC part gives information about the serving and adjacent GSs and the RA part is used to connect to the serving GS. In addition, each MF in the FL direction is divided into nine frames: the four first frames are for payload data, then the variable-size block of Common Control (CC) starts from the fifth frame, and the remaining frames are for payload data. Moreover, an MF in the RL direction is organized into small segments called *tiles*. Each tile belongs to either a Dedicated Control (DC) segment (for signalization) or a Data segment. According to the L-DACS1 specifications [26], a given MS is allowed to use only one RA subframe and only one DC tile per SF. The GS sends in the CC of the first MF the identifier of the DC tile allocated to the MS.

On the other hand, the L-DACS2 frame is divided into five sections. The sections UP1 and UP2 are used only by the GS and the remaining sections (LoG2, CoS1 and CoS2) are employed only by the MS. The beginning of the UP1 section contains information about the serving GS. The LoG2 section is used to connect to the serving GS. When a MS is already connected to the GS, the GS transmits in UP1 the CoS1 slot that will be reserved to that MS (for signalization) and indicates in UP2 the allocated resources. The L-DACS2 frame is composed by 150 equal size transmission units named *basic slots* distributed over the five sections of the frame. To avoid overlapping between RL and FL messages, each slot contains a radio-frequency transmission element called *burst* and a guard time. Within a one-second frame, a MS is allowed to use one LoG2 slot, one CoS1 slot and between one and ten CoS2 slots to transmit data (see [29]) and a GS must use one UP1 slot and one UP2 slot to transmit messages to a given MS.

Based on the information given so far, we have shown **the differences between** the two L-DACS proposals. Each technology has its own advantages and drawbacks and it is difficult to discriminate between them. For this reason, more detailed studies are needed to evaluate them to make the final choice. A scope of such studies is provided in the next section.

V. Before the final L-DACS choice

Unlike the other components of the FCI, the final technology to ensure continental communications is not yet finalized. **In the recent months, L-DACS activities have mainly proceeded within SESAR with the objective to refine the work performed until 2009. In particular, additional studies were initiated on potential interference mitigation techniques, spectrum compatibility criteria, interference scenarios and the testing plan. All these activities, completed with performance evaluation through EMC laboratory tests on prototypes and simulations, will be finalized and presented in the coming months with the objective to support a choice on the L-DACS technology.** As shown in Fig. 3, all these tasks are complementary and dependant on each other. We present in this section the current status of the L-DACS development considering in particular the detailed specifications of LDACS1 and LDACS2, the development of LDACS1 and LDACS2 prototypes and the assessment of their overall performance in realistic conditions through interference scenarios.

A. L-DACS1 and L-DACS2 specifications

Initial systems specifications have been already developed by EUROCONTROL in 2009. Definition documents of both L-DACS systems [26], [29] give detailed description of each candidate and identify the most relevant parameters to take into account. Information about PHY and MAC layers in time and frequency domains have been provided in the previous section of this paper. These specifications may be updated after prototypes' development and tests. **The L-DACS1 specifications have been updated within the early task of SESAR working activities.**

B. L-DACS1 and L-DACS2 prototypes

Based on identified parameters, transmitter and receiver prototypes are being defined. These prototypes, which are also key parts of the L-DACS development, must be in line with the systems specifications.

So far, EUROCONTROL has developed in documents [31] (respectively [32]) transmitter and receiver prototype specifications for L-DACS1 (respectively L-DACS2) for both ground and airborne installations. In parallel, the Japanese ENRI started in April 2009 a research program on L-DACS aiming to develop an L-DACS transceiver using Software-Defined-Radio tools as detailed in [42], [43].

In addition, specific test-beds are being created to evaluate these prototypes. This step is necessary to demonstrate the suitability of L-DACS performance in the presence of interference from existing systems as well as their spectrum compatibility. This aspect is known as the EMC of L-DACS with legacy systems. For the moment, test-beds for L-DACS transmitters **are in the planning phase**.

*C. **L-DACS1 and L-DACS2 performance***

To test the performance of the L-DACS candidate systems in relevant aeronautical environments with respect to requirements [7], the main outputs to be checked are the continuity, the integrity, the availability, the latency, the expiration time, the peak number of users **per L-DACS cell** and the throughput for each user.

Many studies are being currently performed to assess L-DACS capabilities **through different interference scenarios and application/traffic scenarios. The output of interference simulations (such as BER) is also used as an input for capacity and performance simulations.** The EMC analysis is important to complete the selection of the L-DACS solution and includes studies in both ground and onboard environments. Knowing that each aeronautical system includes an onboard equipment and a ground equipment, many interference scenarios should be considered for EMC investigations, as detailed in Fig. 4.

EMC studies determine if an interfering transmitter and a victim receiver can coexist in the same electromagnetic environment. More precisely, the EMC is achieved if the victim receiver performance remains acceptable in the worst case situation, where the equipment is likely to receive the highest interference level from its potential interferers. The number of interferers is large because the future aeronautical network is foreseen to manage the communication among a large number of airplanes [7]. To deal with EMC in such environments, a generic approach is proposed and it consists of five successive steps:

- Identify the interference scenario, the victim receiver and the potential interferers,
- Characterize each interferer by its transmitting parameters (power, central frequency, bandwidth, antenna radiation pattern, cable losses and spectral mask),

- Characterize the victim receiver by its receiving parameters (central frequency, bandwidth, antenna radiation pattern, cable losses, **blocking mask,** sensitivity and system range),
- Define the interference path (relative position between the victim receiver and each potential interferer in space and frequency) and the propagation model,
- Compute the resulting interference level at the victim receiver and compare it to its maximum acceptable level with respect to its performance requirements.

Based on this methodology, number of tests [60]–[65] are being carried out to evaluate the L-DACS performance through various interference scenarios detailed in [66], with different aeronautical and telecommunication systems which are operating either in the L-band or in the adjacent bands. We present in the following subsections the issues that have been raised to perform such studies.

1) How to model the environment?: Two different approaches to model the aerospace environment may be adopted. The first approach comprises static [33], [67]–[69] and statistic [70] models which have been used so far for first and second generation systems for mobile communications. The interference level is computed for example through Monte-Carlo simulations. However, taking into account the airplanes **safety issues**, these methods may not cover the worst case situations of some scenarios mentioned in Fig. 4. The second approach [71] is proposed to analyze these particular situations. It consists of building a **deterministic** model to represent the aeronautical environment, based on number of parameters such as aeronautical regulatory constraints, the minimal distance separation between any two airplanes or any two base stations for example. The paper [72] gives a case study in the air to air scenario. Resulting models strongly depend on radiation patterns of both transmitting and the receiving antennas.

Modeling the environment is more complicated for the co-site scenario, which is the most EMC critical situation because of equipments proximity. One should take into account relative positions of the different devices as well as the effects of the airplane's structure. A tool is being proposed for this particular case in [73] and could be further investigated.

2) How to mitigate the interference?: In addition to transmitting and receiving spectral masks, the interference mitigation is necessary to reduce L-DACS unwanted radiations over other L-band and adjacent equipments, and also to protect L-DACS from unwanted signals of legacy systems. The L-DACS1 and L-DACS2 specifications mentioned several techniques for interference suppression, which can be categorized into three different classes.

The first class includes techniques proposed for L-DACS1 transmitters and adapted to the OFDM modulation. They are described more in details in [74], [75]. Some of them are used in the time domain whereas the others are employed in the frequency domain:

- The *time windowing* consists of multiplying each OFDM symbol by a raised cosine window.
- The *Multiple Choice Sequences* means transmitting several versions of the OFDM symbol and choosing the one with the lowest **out-of-band power** (see Fig. 2).
- The *Cancelation Carriers* technique is to add some carriers which do not transmit data on the right and left of the OFDM symbol.
- The *Sub-Carrier Weighting* principle is to weight each subcarrier transmitting data by a factor between g_{min} and g_{max}.

The second class comprises filtering tools that have been proposed for L-DACS1 receivers. They are explained more explicitly in [75] and are the following:

- *Combination of two digital filters*: this technique reduces the narrowband interference. The first one (time domain) is placed before the OFDM demodulator and the second (frequency domain) is after this block.
- *Soft erasure decoding*: this technique suppresses the received symbols with a very low Signal to Interference plus Noise Ratio (below a fixed threshold).

The third class of techniques represents some filtering methods for L-DACS2 receivers. The system specifications [29] emphasize two main types of filtering:

- *Notch filtering*: this technique suppresses narrowband pulse signals.
- *Hybrid filtering*: this technique detects L-DACS2 pulses (in the time domain) and applies the notch filtering around its estimated carrier. This filter is already used for satellite systems.

3) How to achieve a satisfying EMC?: The first EMC investigations on L-DACS systems have been carried out in the frequency domain. The addressed problem is the frequency sharing between L-DACS and legacy systems. As detailed in [33], [70], [76], the idea is to analyze the highest generated interference density with respect to the spacing between the interferers and the victim receiver central frequencies. The obtained results so far indicate that both L-DACS candidate waveforms could cause potential interference on existing radionavigation systems. In such a situation, *i.e.* when the achieved EMC level is insufficient, many solutions are being studied.

A first option is mentioned in [71], which proposes an additional spatial and/or frequency separation between the victim receiver and its potential strongest interferers. To protect the victim receiver from interfering radiations, it is possible either **to increase the distance between the victim receiver and the interferers** or to reduce the number of in-band interferers, *i.e.* transmitters whose frequency channels overlap with the victim receiver bandwidth.

As the degrees of freedom related to this option is limited (because of the finite allocated spectrum and the increasing density of airplanes), another solution is currently under study in [77] and [78]. According to the specifications of both L-DACS candidates and **legacy L-band systems**, each Radio Frequency (RF) transmission is **pulsed** (so, not continuous) and each device uses the RF channel during a limited period of time, called the channel occupation rate. Hence, in this approach, Electromagnetic Interference (EMI) studies are being performed taking into account the different systems time domain characteristics. When the interferer and the victim receiver are functioning during distinct time intervals, the **probability of interference** is likely to decrease comparing to the frequency-domain case.

A good EMC level is achieved once guaranteed that during a given time slot, only one device transmits/receives signals, or if the performance degradation due to interference is sufficiently low. Actually, this condition may be not satisfied especially for the co-site interference scenario. As a large number of systems are implemented within the same airplane, the collision probability among onboard-generated signals becomes higher and higher. To overcome these undesired effects, the L-DACS specifications mention the possibility to study the implementation of a common suppression bus, which interconnects the airborne L-DACS equipment with onboard other avionics elements. This bus could be activated if a system which could damage other systems or provoke undesired operation, transmits. During this activation, the other onboard equipment transmissions and / or receptions can be blocked. This technique is already proposed for several onboard systems, namely the Universal Access Transceiver (UAT) [79] and the Traffic Collision Avoidance System (TCAS) [80] but no general operating mode of the device is currently provided. Based on these elements, studies are being carried out to assess the potential use of the suppression bus in onboard environments [81].

VI. L-DACS CHALLENGES

The L-DACS is being designed to fulfill all of the new aeronautical requirements and provide better mechanisms to assist the pilot and increase flight safety. However, this system has to meet number of challenges before its deployment and some aspects of its development still need to be more analyzed before its implementation. In the previous section, we focused on EMC / EMI investigations, which is one of the most important areas to be studied to ease the **L-DACS development**. We recall this aspect in this section and we present several other main challenges for further stages of the L-DACS development.

A. Standardization

The L-DACS system, being a part of the proposed FCI, is expected to be a global system for aeronautical safety continental communications. As a result, it is expected that L-DACS will be **globally** deployed in the long term. For this reason, an important multinational cooperation will be necessary and international standards and recommended practices will also have to be developed by the ICAO for this communication system.

B. EMC Conformity

As far as standardization is considered, one of the key questions to be addressed is the EMC of L-DACS with existing systems in both ground and airborne environments. The task is particularly important because any **disfunction** in the communication can threaten the flight safety. Not only must the candidate systems be able to operate in the presence of interference from other equipments, but they must also cause the minimum possible interference to legacy systems. Some of these systems in the 960-1215 MHz band are illustrated in Fig. 5.

Most of them are other aeronautical systems but they also include telecommunication as well as satellite systems (these two latter are using adjacent frequency bands to the L-DACS spectrum). In the following, we give a brief description of each system herein mentioned.

- The Distance Measuring Equipment (DME) [82] which evaluates the **slant range** between an airplane and a ground beacon by measuring the return ticket of **gaussian shaped pulse pairs**,
- The Tactical Air Navigation (TACAN) which is **similar** to the DME,

- The UAT [83] which exchanges data related to the traffic state and weather conditions,
- The Secondary Surveillance Radar (SSR) [84] which identifies airplanes and **provides information about** the flight's speed, altitude and state,
- The other non-ICAO ARNS which refer to national radionavigation systems,
- The GSM in the 900 MHz band, which is a second generation system for mobile telephony that is standardized by the European Telecommunications Standards Institute (ETSI) and is used in Europe, Africa, Mideast and Asia,
- The Universal Mobile Telecommunications System (UMTS) in the 900 MHz band, which is a European third generation system for mobile telephony that is standardized by the Third Generation Partnership Project (3GPP). Other broadband electronic communication means may be deployed in the future.
- The Global Positioning System (GPS) L5 [85] which is a worldwide localization system that uses satellite **signals**, characterized by the Radio Technical Commission for Aeronautics (RTCA) DO-292 working group,
- The Galileo E5a and E5b signals [85] which are **new types of signals similar to the GPS L5 signal** and standardized by the European Organization for Civil Aviation Equipment (EUROCAE) Working Group 62 commission.
- The Joint Tactical Information Distribution System (JTIDS) and and the Multifunctional Information Distribution System (MIDS) [86] which are **radiocommunication systems authorized by some administrations.**

All these systems have different performances and independent functioning modes. Moreover, many among these systems (and others in other frequency bands like VHF) are foreseen to operate in the same airplane. Therefore, the EMC conformity becomes more and more complex.

C. Radio Resource Optimization

Once the EMC step is achieved, it is important to find the optimal way to **manage the total allocated spectrum to AM(R)S**. The radio resources allocation is related to the transmission peak/average power, the transmission channel bandwidth and the channel occupation rate, that is the percentage of time during which a user is allowed to transmit its messages. Indeed, the network capacity (being herein the number of airplanes simultaneously connected **to the particular L-DACS ground station**) could be maximized by optimizing the frequency planning

as well as L-DACS protocols, and by minimizing interference levels between users through a control of the airplane transmitted power. However, this latter may have to be balanced with the fact that having more airplanes in the same network may increase interference phenomena. Hence, a trade-off between the interference minimization and the capacity maximization should be found for the radio resource optimization.

D. Air Traffic Growth

As mentioned in the Section II, the design of L-DACS candidates and their associated requirements are based on the **air** traffic forecast for the next decades, depending upon statistical studies performed by aeronautical authorities throughout the world. L-DACS1 and L-DACS2 are then considered as a long term best-performer solution for L-band continental communications. Therefore, they should be able to fulfil this long term communication demand.

VII. Conclusion

In this survey, we showed that the future aeronautical communication system will have to provide many interesting services for both pilots and controllers and to cope with the VHF spectrum congestion, meeting new requirements formulated by aeronautical authorities, and introducing new applications and concepts in aviation. We emphasized that the future communication infrastructure will use various technologies across different frequency bands to support both data and voice demand for the upcoming years. In particular, we emphasize that the L-DACS system has been chosen for continental communication. The L-DACS development motivated researchers, industrial partners and aeronautical instances from different continents around the world. According to technology assessment results, no existing technology could provide optimal performance with respect to the evaluation criteria, and consequently two options have been currently preselected to support this system. The two L-DACS proposals are very different, in particular at PHY and MAC layers, but both are promising as they fulfill aeronautical requirements and take advantage from the best existing technologies. Before the final L-DACS choice, in-depth studies are being performed to develop L-DACS1/2 prototypes and to assess their performance through evaluation scenarios as well as interference scenarios. More particularly their coexistence with all the numerous systems that have been already operating in the aeronautical L-band

and its adjacent bands is important. Some other aspects of its development should also be more analyzed before L-DACS implementation. Therefore, joint efforts are being made to develop L-DACS, address its different development issues and overcome eventual risks of its deployment. The subsequent work is to select the final L-DACS solution and continue on the road of L-DACS development through multinational cooperation.

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[86] International Telecommunication Union - Radiocommunication Sector, “Results of studies of the AM(R)S allocation in the band 960-1 164 MHz and of the AMS(R)S allocation in the band 5 030-5 091 MHz to support control and non-payload communications links for unmanned aircraft systems,” 2010, recommendation ITU-R M.2205.

[87] Electronic Communications Committee (ECC) - European Conference of Postal and Telecommunications Administrations (CEPT), “Proposed amendments to the Working Document towards a Preliminary draft new report ITU-R M. on AM(R)S sharing feasibility in the 960-1164 MHz band,” 2008, doc. ECC/CPG11/PTC(2008)45 - Annex 04.

TABLE I

L-DACS1 AND L-DACS2 MODULATION AND MAIN SYSTEM PARAMETERS

L-DACS1 modulation		
Parameters	*Values*	*Units*
FFT size (Total number of subcarriers)	64	
Number of useful subcarriers	50	
Number of subcarriers for the cyclic prefix	**11**	
Cyclic prefix time	**17.6**	μs
Modulated symbol duration	120	μs
Inter subcarrier spacing	9.765625	kHz
L-DACS2 modulation		
Parameters	*Values*	*Units*
Modulation index	0.5	
BT product	0.3	
Modulated symbol duration	3,6923	μs
System Parameters	***L-DACS1***	***L-DACS2***
System range	200 NM	200 NM
Airborne cable loss	3 dBi	3 dBi
Physical BER	**not specified**	10^{-3}
Residual BER	10^{-6}	10^{-7}
Transmitting effective bandwidth	498,05 kHz	200 kHz
Maximum ground transmit power	46 dBm	55,4 dBm
Maximum airborne transmit power	46 dBm	47 dBm
Ground cable insertion losses	2 dB	2.5 dB
Receiving effective bandwidth	498,05 kHz	200 kHz
Ground noise **figure**	5	7
Airborne noise **figure**	6	10

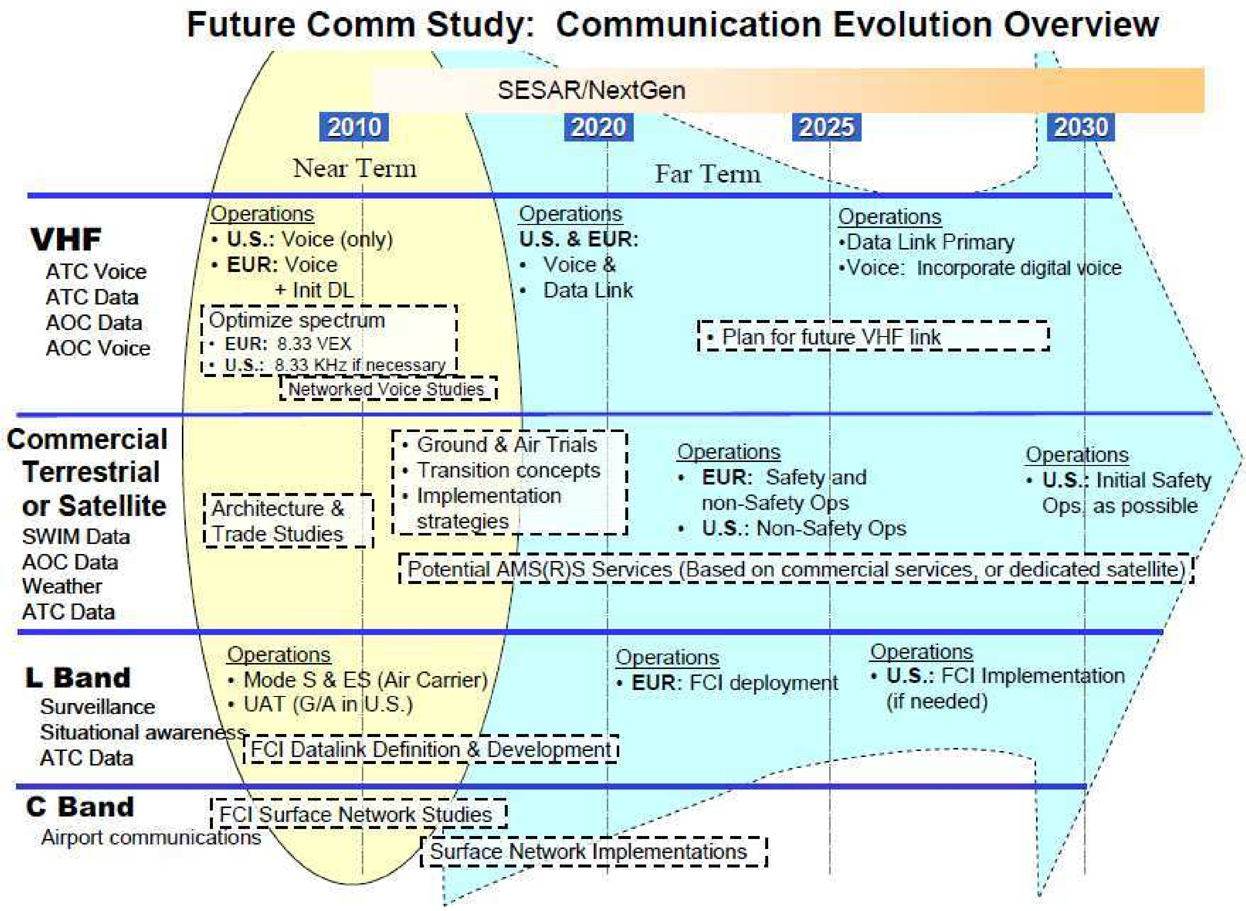

Fig. 1. The aeronautical communications evolution roadmap in Europe and the United States (source [25])

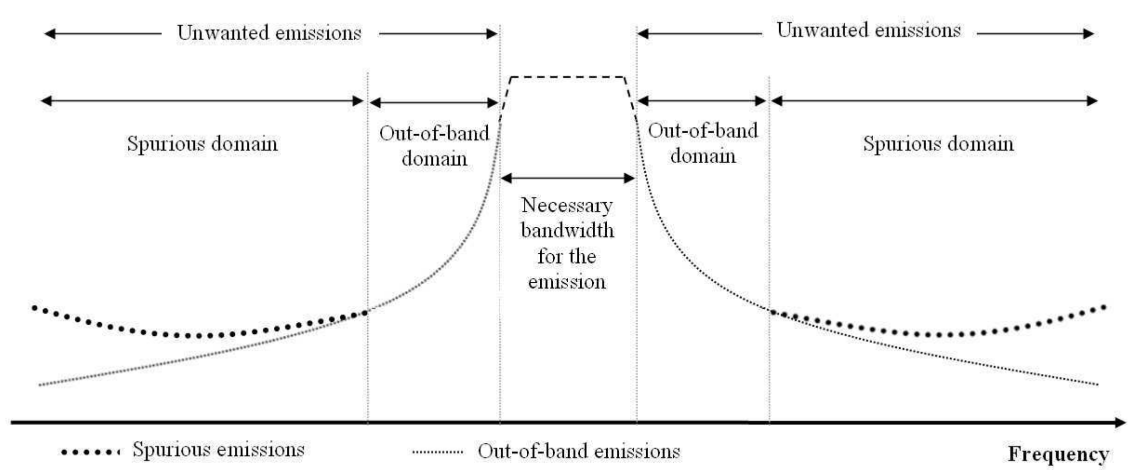

Fig. 2. Unwanted emissions description

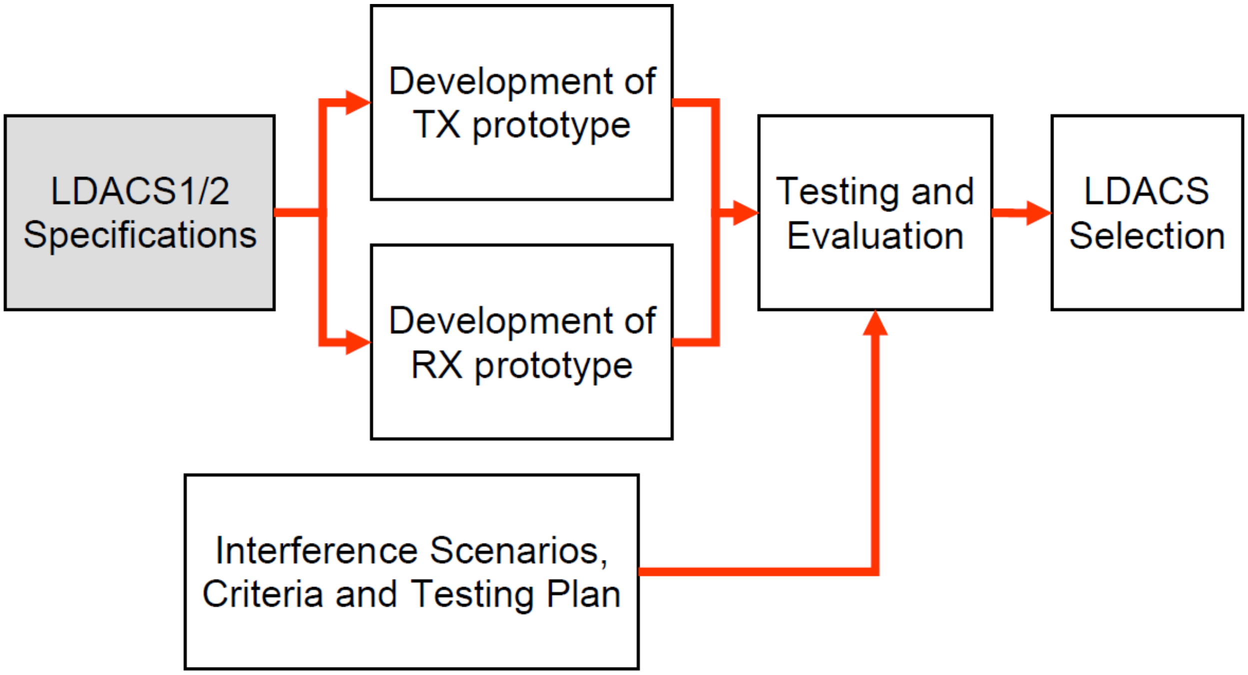

Fig. 3. The applied process for the L-DACS selection (sources [26], [29])

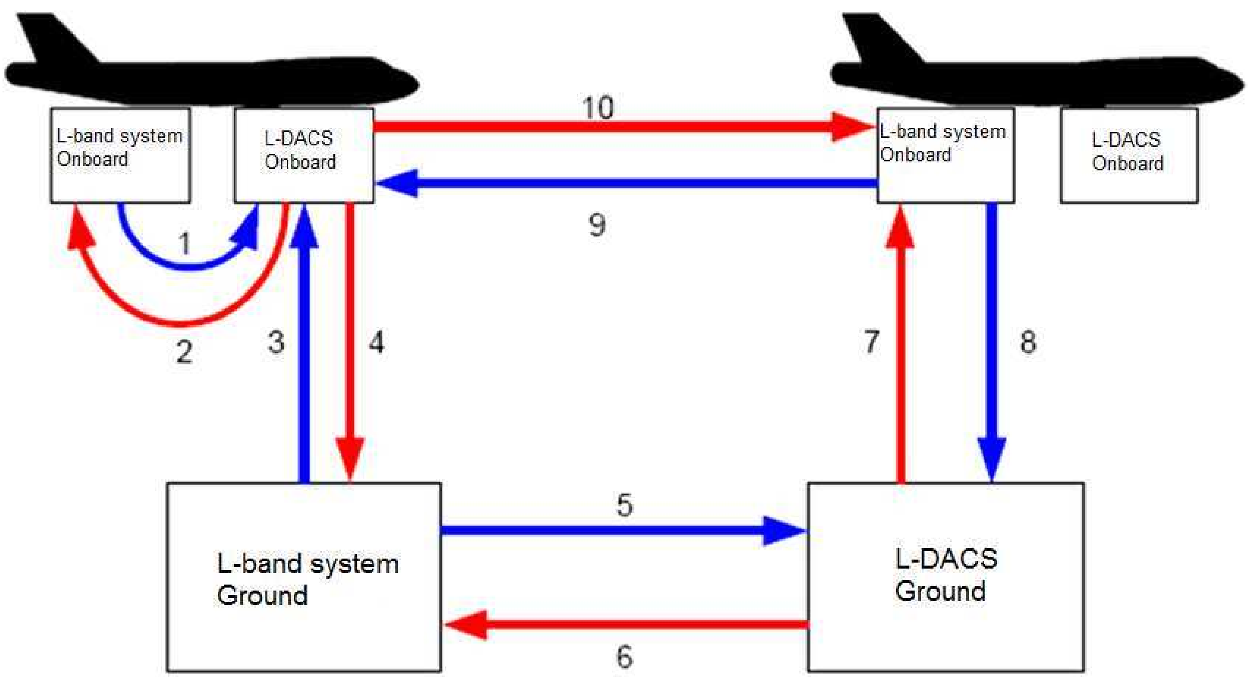

Fig. 4. List of the interference scenarios between L-DACS and L-band systems

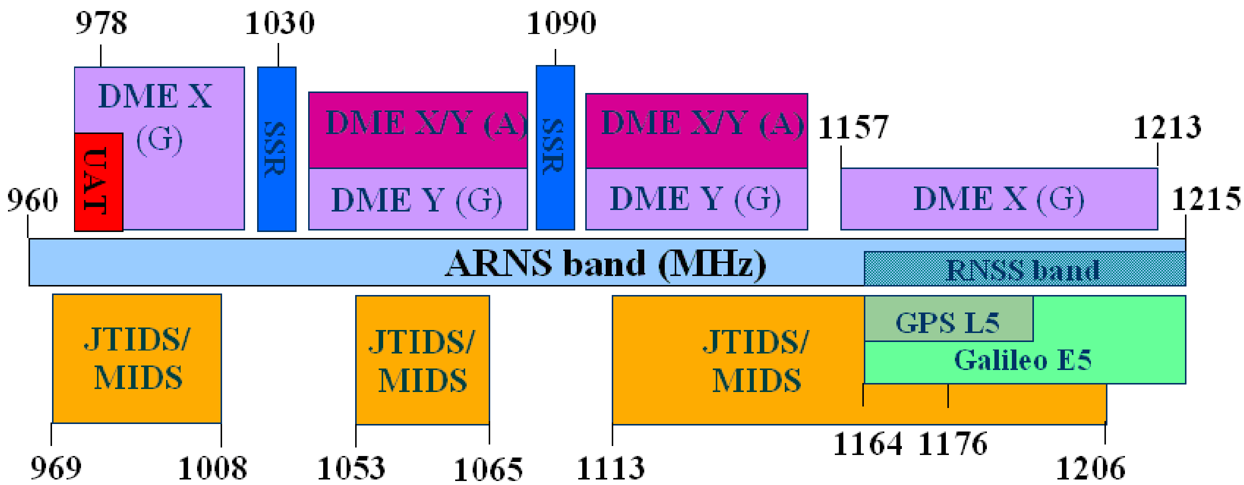

Fig. 5. The L-Band spectral occupancy (adapted from [87])

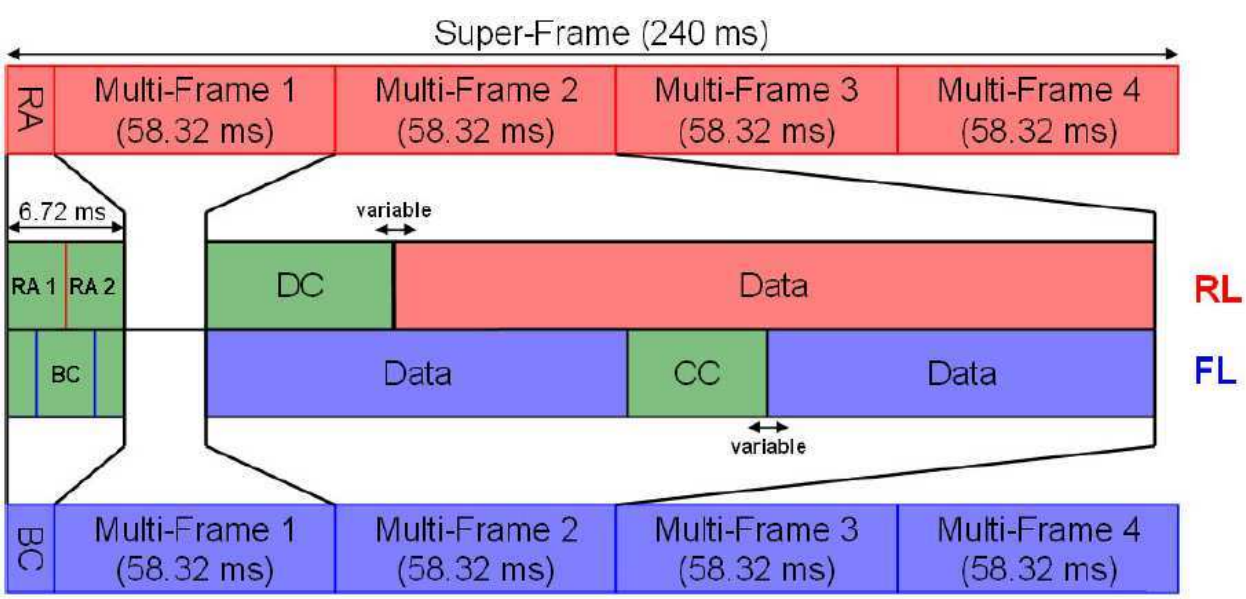

Fig. 6. The L-DACS1 frame structure (source [26])

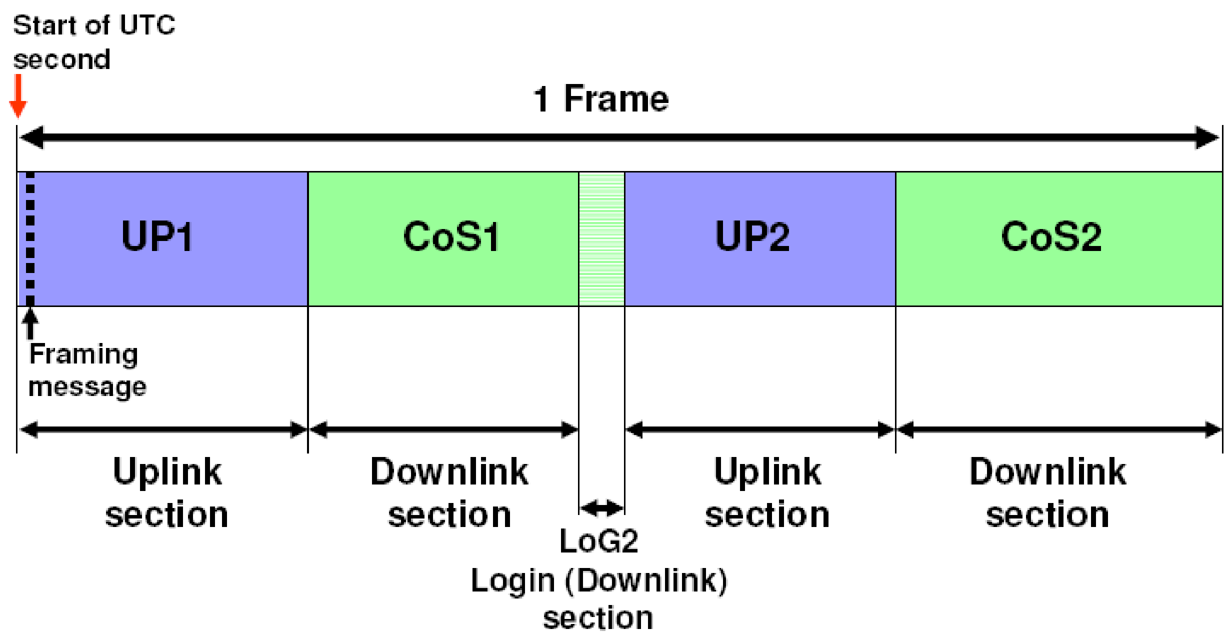

Fig. 7. The L-DACS2 frame structure (source [29])